Elaboration of Tool for Production Process Reliability Evaluation in Machinery Industry

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***Abstract*-In this paper it is given an overview of a tool which was elaborated for estimation of production process reliability specifically for machinery enterprises. The main goal was to develop the reliability assessment tool which must help engineers quickly and with a great precision estimate most unreliable places of a production process and to indicate ways of them elimination with great efficiency. Work of this tool is based on Failure Mode and Effects Analysis (FMEA) method which is combined with Belief Bayesian Networks (BBN). By-turn FMEA method is extended by faults causes and method of expert opinion assessment. First allows classifying faults causes and transferring the information from FMEA to BBN, and second allows estimating FMEA parameters more precisely and therefore get more accurate prediction in BBN. In the last part of the paper an example of this tool working is proposed.**

I. INTRODUCTION

In today's competitive environment it is not enough only to produce and sell goods. Companies are forced to track and reduce wastes inside the production in order to maximize profit. One of the sources to achieve this is reliable production process. Reliable production process means less scrap, better quality, less downtimes so it is essential that the objective of any factory is to increase the overall production reliability. Nowadays there are a lot of different methods for reliability estimation and improvement however Small and Medium Enterprises (SMEs) often encounter with difficulties to implement reliability principles in production due to complexity of methods and huge requirements of resources. In addition the situation becomes more complicated because SMEs often think about implementation of reliability principles when production process has already been starting, however most of reliability methods give the most benefit when they are implemented during designing of a production process. Another not the least of the factors is cost of software of those methods, it often requires significant investments. In our tool Failure Mode and Effects Analysis (FMEA) is taken as a base which can be done even in Excel. Thus the tool described further can become a good alternative for SMEs.

II. STRUCTURE OF THE TOOL

Realistically, it is impossible to avoid all feasible failures of a system or a product on the design stage, so one of the goals of reliability engineers is to recognize the most expected failures inside a production process and then to identify appropriate actions to mitigate the effects of those failures [1].

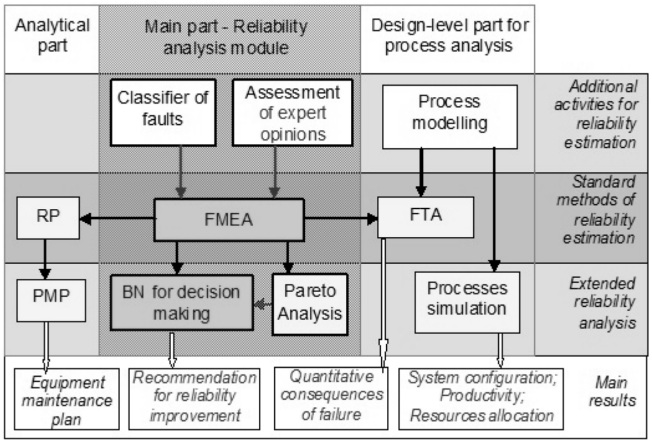

Fig. 1. Tool of a manufacturing process reliability assessment.

The proposed reliability estimation tool includes three main parts (Fig. 1):

1. Reliability analysis module – the main part;
2. Design-level part for process analysis;
3. Analytical part.

Every part is considered on the following levels:

- Standard methods for reliability assessment;
- Additional activities for reliability assessment;
- Extended reliability analysis.

The standard methods used in this tool are based on an international standard proposed in Electronic Reliability Design Handbook [2]:

- Fault Mode and Effects Analysis,
- Fault Tree Analysis (FTA),
- Mathematical Reliability Prediction (RP).

The reliability analysis module enables:

- to calculate the max/min boundaries of an error probability for a selected production route;
- to define the most critical faults that influence the production route reliability;
- to select the most efficient corrective actions for the production route reliability improvement.

III. RELIABILITY ANALYSIS MODULE

This part is the main part of this research. In the centre of the tool is FMEA, other methods are based on the data from this analysis. Therefore the analysis must be implemented as precisely as possible. An assessment of expert opinions is used for the evaluation of the more significant parameters of FMEA. Especially it's important for such a parameter as fault severity.

A. The Failure Mode and Effects Analysis

The Failure Mode and Effect Analysis (FMEA) is a reliability procedure which documents all possible failures in a system design within specified ground rules. It determines, by the failure mode analysis, the effect of each failure on the system operation and identifies single failure points, which are critical to the mission success or crew safety [3].

In general the FMEA is a systemized group of activities designed to

- recognize and evaluate the potential failure of a product/process and its effects,
- identify actions, which could eliminate or reduce the chance of a potential failure occurring,
- document process

The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones. It may be used to evaluate risk management priorities for mitigating known threat-vulnerabilities. In the FMEA failures are prioritized according to three dimensions:

1) How serious their consequences are,
2) How frequently they occur,
3) How easily they can be detected.

Used properly- the FMEA methodology allows identifying and documenting the potential system failures and predict the consequences resulted. It would enable to determine the actions that would reduce severity and occurrence, but increase the detection of the potential failures. The composite risk score for each unit operational step is the product, that combines three of its three individual component ratings: Severity (S), Occurrence (O) and Detection (D). This composite risk is called a risk priority number (RPN) "(1)". This number is then used to rank the order of various concerns and failure modes associated with a given design, as previously identified in the FMEA.

$$RPN = (S) * (O) * (D) \qquad (1)$$

The RPN is a measure of a design risk. The RPN is also used to rank the order of the processes' concerns. The RPN will be between "1" and "1,000." For higher RPNs a team must undertake efforts to reduce this calculated risk through a corrective action(s).

Advantages:

- Identifies connections between reasons and effects;
- Takes into account the failure severity;
- Demonstrates previous unknown event outcomes;
- It is a systematized analysis;
- Provides focus for an improved testing and development;
- Minimizes late changes and the associated cost;
- It is a catalyst for teamwork and the idea exchange between functions.

Disadvantages:

- The number of data can be quite big
- The analysis can become rather complicated,
- The environment and maintenance conditions cannot be examined.

In our research the outcome of the FMEA is a list of recommendations to reduce the overall risk to an acceptable level, so that it can be used as a source for designing of a control strategy. The FMEA data may also be used in other types of a reliability analysis, Fig. 1.

B. Assessments of Expert Opinions

Assessments of expert opinions are used for more precise estimation of the FMEA parameters. This approach is needed when the expert opinions do not match.

The FMEA method implementation may be characterised as activities of an organised group. The initiation of the FMEA requires assembling of a team, usually comprised of a facilitator, a team leader, and functional experts from development, manufacturing, quality, regulatory, etc. The assembled team should first describe the process of unit operations in general, then section each unit operation into its component parts and estimate every part by its main parameters. During the estimation of the parameters, especially the faults severity, experts' opinions often diverge. In the current work we suggest to use the consistency assessment of the expert opinions for increasing the quality of the estimation of the FMEA parameters.

Proposed by Maurice G. Kendall and Bernard Babington Smith, Kendall's coefficient of concordance (W) is a measure of the agreement among several quantitative or semi-quantitative variables that are assessing a set of n objects of interest **[4].** The Kendall coefficient of concordance can be used to assess the degree to which a group of variables provide a common ranking for a set of objects. It should only be used to obtain a statement about variables that are all meant to measure the same general property of the objects [5].

The consistency of the opinions of experts can assess the magnitude of the coefficient of concordance. The coefficient of concordance varies in the range of $0 < W < 1$:

- 0 - the total incoherence, 1 - complete unanimity.
- If $W \geq 0{,}7 \div 0{,}8$ opinions are consistent,
- If $W < 0{,}2 \div 0{,}3$ opinions are not consistent,
- If $W = 0{,}3 \div 0{,}7$ average consistency.

$$W = \frac{12S}{n^2(m^3 - m)} \qquad (2)$$

where n – a number of experts;
m - a number of objects of expertise.
S - a sum of squared deviations of all the examination objects' rank estimates of the mean;

$$S = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} x_{ij} - \frac{1}{2} m(n+1) \right)^2 \qquad (3)$$

where x_{ij} – the rank assigned to the i-th object j-th expert.

C. The Classifier of Faults

The classifier of faults (Fig. 2) is needed for a fault ordering in machinery enterprises. It must help engineers, by the codes of faults, to define quickly the causes of faults. These codes are included in the FMEA. On the base of this classifier it is possible, quite easily, to build the Bayesian Belief Network (BBN) for a process, because the structure of BBN is the same as the one of a classifier with the faults revealed by the FMEA of the process.

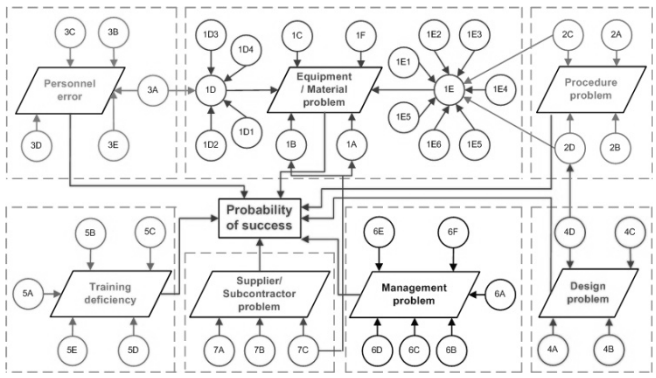

Fig. 2. The classifier of faults.

Reliability engineering is dealing with analysis of the causes of the faults in the factories. For this reason was used as a base DOE-NE-STD-1004-92 standard [6]. The assessment phase includes analyzing the data to identify the causal factors, summarizing the findings, and categorizing the findings by the cause categories. The major cause categories are:

- Equipment/Material Problem
  - 1A Defective part
  - 1B Defective material
  - 1C Software failure
  - 1D Equipment failure
    - 1D1 Component damage
    - 1D2 Fuse burn
    - 1D3 Circuit fault
    - 1D4 Looseness
  - 1E Bad equipment work
    - 1E1 Machine tool leveling
    - 1E2 Cutting conditions
    - 1E3 Inhomogenities in the work material
    - 1E4 Disturbance in machine tool drivers
    - 1E5 Machining process
    - 1E6 Tool setting, job holding
    - 1E7 Bad adjustment
  - 1F Contamination
  - 1J Critical human error
- Procedure Problem
  - 2A Inadequate procedure
  - 2B Lack of procedure
  - 2C Error in equipment/material selection
  - 2D Error in tool/cutting data selection
- Personnel Error
  - 3A Inadequate work environment
  - 3B Inattention to detail
  - 3C Violation of requirement or procedure
  - 3D Verbal communication problem
- Design Problem
  - 4A Inadequate design
  - 4B Drawing/specification/data errors
  - 4C Dimensions related problem
  - 4D Technological parameters problems
- Training Deficiency
  - 5A No training provided
  - 5B Insufficient practice/nand-on experience
  - 5C Inadequate content
  - 5D Insufficient refresher training
  - 5E Inadequate presentation/material
- Management Problem
  - 6A Inadequate administrative control
  - 6B Work organization/planning deficiency
  - 6C Inadequate supervision
  - 6D Improper resource allocation
  - 6E Policy not adequately defined
  - 6F Other management problem
- Supplier problem
  - 7A Communication problems
  - 7B Time delivery error
  - 7C Defective product/material

Those seven elements are necessary to perform any task, related to equipments, procedures (technology) and personnel. We have adapted the classifier from this document for machinery enterprises, see Fig. 2.

Two new fields, such as “Failure class” and “Cause code” are included in the FMEA.

D. *Bayesian Belief Network*

BBN is a graphic probabilistic model through which one can acquire, capitalize on and exploit knowledge. It consists of a set of interconnected nodes, where each node represents a variable in the dependency model and the connecting arcs represent the causal relationships between these variables [7, 8].

We decide to use the BBN in our research because the structure of BBN is the same as a faults’ classifier. Reliability engineers must, only, by using the existing FMEA and cause codes, create the same structure of BBN and include into every node the probability of particular cause errors. The Bayesian networks are natural successors of statistical approaches to Artificial Intelligence and Data Mining. Particularly suited to taking uncertainty into consideration, they can be easily described manually by experts in the field.

A Bayesian network is a graphical model that encodes probabilistic relationships among variables of interest. When used in conjunction with statistical techniques, the graphical model has several advantages for data analysis, because [9]:

- the model encodes dependencies among all variables, it readily handles situations where some data entries are missing;
- the Bayesian network can be used to learn causal relationships, and hence to gain understanding about a problem domain and to predict the consequences of intervention;.
- the model has both, causal and probabilistic semantics, it is an ideal representation for combining prior knowledge (which often comes in a causal form) and data;.
- Bayesian statistical methods, in conjunction with the Bayesian networks, offer an efficient and principled approach for avoiding the over-fitting of data.

In this research the BBN is used to analyze the effect that the improvement of different fault groups will take. In BBN, the decision-maker is concerned with determining the probability that a hypothesis (H) is true, from evidence (E) linking the hypothesis to other observed states of the world [10]. The approach makes use of the Bayes' rule to combine various sources of evidence. The Bayes' rule states that the posterior probability of the hypothesis H, given that evidence E is present or P(H|E), is

$$P(H|E) = \frac{\mathrm{I}(E|H)P(H)}{P(E)} \tag{4}$$

where $P(H)$ is the probability of the hypothesis being true prior to obtaining the evidence E and $P(E|H)$ is the likelihood of obtaining the evidence E, given that the hypothesis H is true.

When the evidence consists of multiple sources denoted as 1 2 *n E*,*E* ,…,*E* , each of which is conditionally independent, the Bayes' rule can be expanded into the expression:

$$P(H|\bigcap_j E_j) = \frac{\prod_{j=1}^{n} P(E_j|H)P(H)}{\prod_{j=1}^{n} P(E_j)} \tag{5}$$

IV. Design-Level Part for Process Analysis

A. Process Modeling and Simulation

Process modelling and simulation are used for a process visualisation and execution of a dynamic analysis of a system. The purpose of any model is to increase an understanding and a reasoned decision making from a model. It helps to support and improve the process.

Enterprises are competing in the environment, which requires the ability to rapidly reconfigure an enterprise and its processes. This ability requires modelling methods to support an analysis and design in multiple aspects of a process performance and structure.

The purpose of modelling and simulations:

- analysis and understanding of the observed phenomena;
- testing of hypotheses and theories;
- prediction of the systems' behaviour under various conditions and scenarios.

For the analysis of manufacturing processes more suitable are structural modelling methods based on the IDEF standard. The IDEF0 modelling technique could test and evaluate each product and process alternative. [11]

There are several common measures of performance, obtained from a simulation study of a manufacturing system, including [12]:

- Throughput
- Time in system for parts (cycle time)
- Times parts spend in queues
- Times parts spend in transport
- Sizes of in-process
- Utilization of equipment and personnel FTA

Fault Tree Analysis (FTA) determines which failure modes at one level produce critical failures at a higher level in the system.

FMEA and FTA have three main differences: boundaries of the analysis, direction of analysis, and presentation of the analysis process and results. FMEA deals with single point failures, is built bottom-up, and is presented as a rule in the form of tables. FTA analyzes combinations of failures, is built top-down, and is visually presented as a logic diagram. By taking into account combinations of failures, FTA avoids the obvious shortcomings of FMEA.

A numerical analysis is performed on the basis of a fault tree. A faultless condition of a system, its usability parameters are estimated using the methods of Boolean algebra. The basic data required for the calculations are as follows: fault rates of parts, repair rates, probabilities of fault modes etc [13].

FTA analysis may be performed independently or in common with FMEA. In our research we suggest to perform FTA analysis on the base of process model, because they both have the same hierarchy structure and can be easily joined.

V. Case Study

In case study we tried to implement reliability module into a process of production route selection and finally combine everything with ERP system (Fig. 3.) In this case the reliability module allows calculating probability of a failure on the top level of the process and getting a list of recommended action for reliability improvement.

The operational data of an enterprise is managed by an integrated cross-functional ERP system. The integration is made through a data base shared by all functions and data processing applications in the company. The operational data required for analysis and reporting is replicated to Data Warehouse (DW) [14].

By using the special capacities of the DW it is possible to select a more suitable route (routes) for elaboration of a new production process for the needed part or product. When the appropriate production route is discovered, the process of the route modification for a particular order is started in the Reliability analysis module.

This level enables to perform it by combining the FMEA method with the BBN approach. FMEA provides data about all possible failures at work station (WS) and BBN allows to prioritize work with these failures and to estimate improvement of reliability of the production route. At this level analysis starts from receiving the percentage of WS faults from DW where this data is collected. For this purpose the number of products with defects produced by every WS divided by total number of product produced. If suggested percentage of faults is within the level required by customer, work with reliability analysis module is finished. If percentage of faults is too high the causes must be analysed [15]. For this purpose the posterior probability boundary is calculated, based on the assumption that the error took place. The calculation of the max/min boundaries of the error probability for the selected operation of a production route shows the most critical fault types, that influence the production route reliability, and enables a decision maker to select the most efficient corrective actions for the causes with the maximum influence of the production route operation reliability improvement.

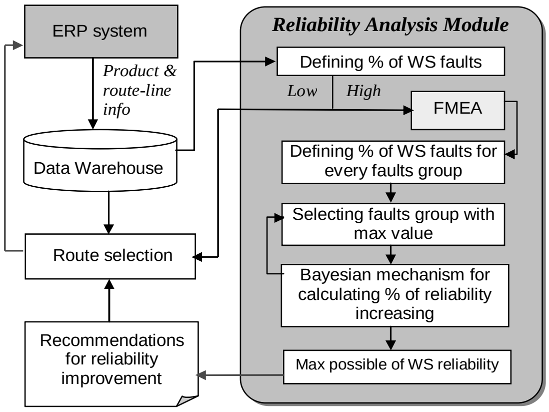

Fig. 3. Combination of a reliability analysis module and the ERP system for a production route selection.

After the required level of reliability is achieved the decision maker chooses the most suitable production route, that further is imported to the ERP system and then into production

The reliability improvement process consists of the following steps:

Step 1 - Definition of failure types. The preparation process is started by definition of possible failure types and adaptation of a classifier under the requirements of a selected enterprise.

Step 2 - FMEA elaboration. This process was started from the analysis of production system operations and particular enterprise requirements.

Step 3 - Analysis of FMEA data and faults probability calculation. The probability of an error for every fault group is calculated on the base of the FMEA by the following equation:

$$P_{PR} = \left(\sum RPN_{PC} / \sum RPN_{Total}\right) * 100\% \qquad (6)$$

where:
P_{RP} – Probability of production route errors,
$\sum RPN_{PC}$ – RPN value for a particular cause of errors,
$\sum RPN_{Total}$ – Total RPN value of a production route.

Step 4 – Building BBN. The BBN is build on the base of an elaborated classifier. To every node of the network it is necessary to include the value of a particular cause error probability. The probabilities on some nodes are affected by the state of the other nodes depending on causalities.

Step 5 – Finding a more effective way to increase the operation reliability by using the BBN analysis.

Step 6 – Including more reliable operations to the production process.

An example of BBN is introduced in Fig. 4. According to Fig. 4 the personnel error is the most probable failure type.

The BBN can answer questions like: if a personnel error exists, was it more likely to be caused by an inadequate work environment, inattention to detail, or violation of requirements. Particularly, inattention to details, which is one of the personnel errors, has the highest probability. Therefore, corrective actions are focused on this failure cause, aiming to decrease it as much as possible. Four corrective actions are planned: Poka-Yoke, visual instruction, improvement of route card and additional training.

In order to make this analysis, the RPN of a corrective action was taken from the FMEA and imported to the Bayesian model. The influence of failure severity was also taken into account. After the calculation it was got that implementation of Poka-Yoke gives us the best result with the least probability of failure.

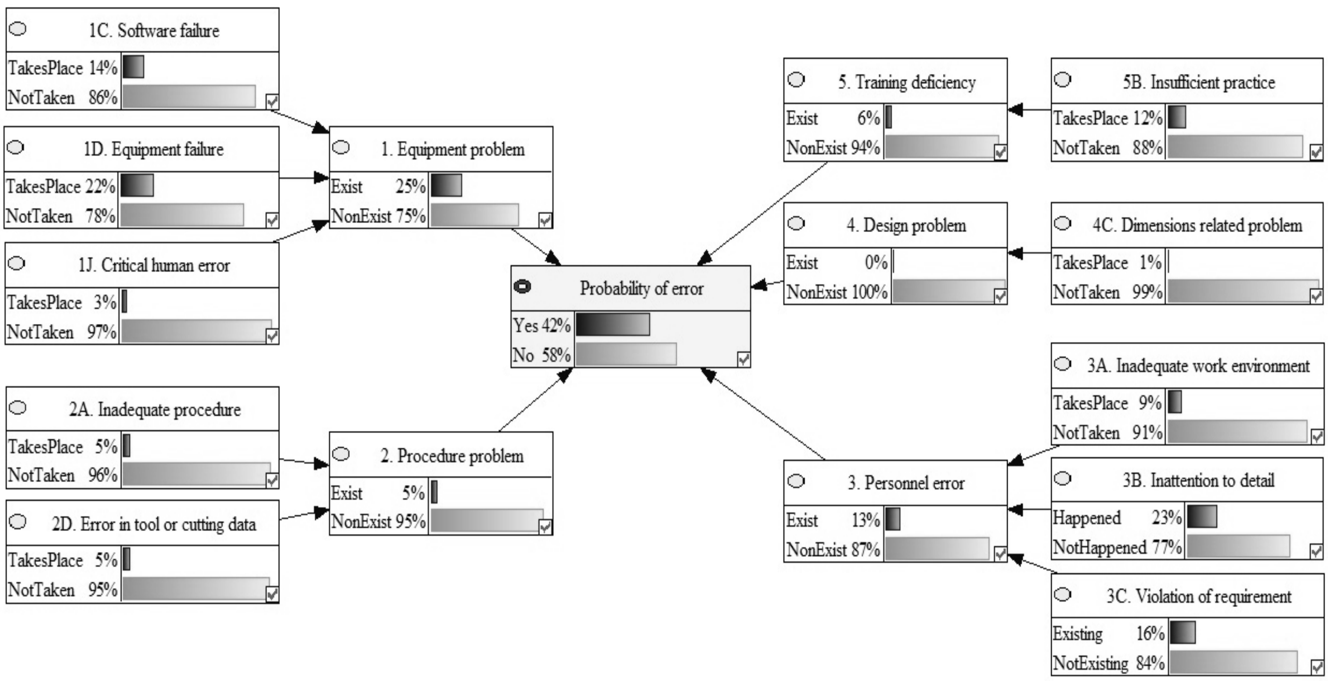

Fig. 4. An example of Bayesian Network.

VI. Conclusion

An integrated modelling method based on a system modelling and complemented with a reliability evaluation mechanism has the capability to analyse and design manufacturing systems. The tool developed to analyse a production process enables companies to analyse the process as a whole and its parts and get an efficient prognosis for the production process reorganization.

In this paper a reliability analysis module was developed in order to increase the reliability of a selected production route. The reliability analysis framework was developed for machinery manufacturing enterprises. The Bayesian Belief Network makes it possible to calculate posterior probabilities of each fault group on the error probability of the manufacturing process.

Acknowledgment

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